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THE EFFECT OF ORIENTATION AND THE PRESENCE OF SURFACE ACTIVE MATERIALS ON THE FRICTION, DEFORMATION AND WEAR OF ALUMINUM

by Donald H. Buckley

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ABSTRACT

Sliding friction experiments were conducted on single crystal and polycrystalline aluminum surfaces. The influence of the following on friction, deformation and wear were determined: (1) orientation of single crystals and textured polycrystalline sheet, (2) liquid metal embrittlement, (3) surface active organics, and (4) alloying with silver. Results indicate that friction and wear of aluminum is highly anisotropic. With single crystals, friction and wear are sensitive both to atomic plane and crystallographic direction of sliding. The presence of embrittling liquid metals on the surface of aluminum was found to reduce surface deformation during sliding. The presence of organic acids and alcohols were found to increase the deformability of oxidized aluminum surfaces.

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SUMMARY

Sliding friction experiments were conducted with hemispherically tipped aluminum crystals or a sapphire ball sliding against single crystal and polycrystalline aluminum. The objectives were to determine the influence of (1) orientation and texturing on friction and wear, (2) the effect of embrittling metals on the deformation of aluminum during sliding, (3) the influence of surface active organics on the deformation of aluminum with sliding, and (4) the effect of aluminum on the deformability of silver. Studies were made over a range of loads from 8 to 250 grams and at a sliding speed of 0.005 millimeter per second. All experiments were conducted at room temperature. The environments in which aluminum were examined included air, mercury, mercury containing various percents of other metals, hexadecane and hexadecane containing various surface active organics. to P20

Results of this investigation indicate that the friction and wear properties of single crystal and textured polycrystalline aluminum are anisotropic. The presence of embrittling liquid metals on the surface of aluminum were found to reduce friction, deformation and wear during sliding. With organic fluids, the presence of surface active organic acids and alcohols increased surface deformation during sliding (see section Rebinder Effect).

INTRODUCTION

Aerospace mechanisms have parts made of aluminum requiring lubrication. Generally the metal is in the form of an alloy and frequently the surface of the alloy has been anodized to reduce adhesion, friction and wear. Despite its relatively wide use, little is known about the fundamental friction and deformation behavior of aluminum during sliding.

In order to understand the influence of the properties of the metal and the effects of the environment on its friction and wear, it is of advantage to examine first pure (99.999 percent) aluminum rather than one of its alloys. Such studies can serve as a point of reference for the understanding of the behavior of alloys used in engineering applications.

During the sliding process, texturing (preferred orientation) of metal surfaces frequently occurs (ref. 1). Some understanding of the anisotropic nature of friction of aluminum would be helpful in predicting the friction behavior of various surface textures. This can be accomplished by examining single crystals of aluminum of various orientations as well as textured polycrystalline surfaces. While the influence of orientation has been examined for some metals (refs. 2 to 5), it has not been done for aluminum.

With sliding under most environments (with the exception of vacuum), films of various types are present on solid surfaces. These surface films have a profound influence on friction as well as on the nature of the deformation process. The presence of surface films can influence the properties of solids by various mechanisms. These include (1) increase in strength by dissolution of the solid surface, "the Joffe Effect" (ref. 6), (2) surface hardening, "Roscoe Effect" (refs. 7 and 8), (3) surface softening, "Rebinder Effect" (refs. 8 to 14), and (4) liquid metal embrittlement (ref. 15).

The objectives of this investigation were to determine for aluminum in sliding friction experiments the influence of the following factors on friction and deformation: (1) orientation of single crystals and textured polycrystalline sheet, (2) liquid metals, (3) hard surface oxide, and (4) surface active organics. The influence of aluminum on the deformation of silver was also examined. Experiments were conducted with hemispherical aluminum crystals or a sapphire ball sliding against single crystal and polycrystalline aluminum. Sapphire was selected for its hardness in order to achieve considerable plastic flow during sliding. The sliding velocity employed was 0.005 millimeter per second with loads from 8 to 250 grams on the aluminum crystal or sapphire ball.

APPARATUS

The apparatus used in this investigation is shown schematically in figure 1. The apparatus consisted basically of a MicroBierbaum hardness tester to which a drive motor was attached in order to provide uniform motion at 0.005 millimeter per second of the crystal specimen under examination.

The rider specimens were a sapphire ball or aluminum crystal 1.6 millimeters in diameter. The arm containing the rider had a strain gage assembly for measuring frictional force. The sapphire ball or aluminum crystals were loaded against the aluminum flat by the application of dead weights directly over the rider.

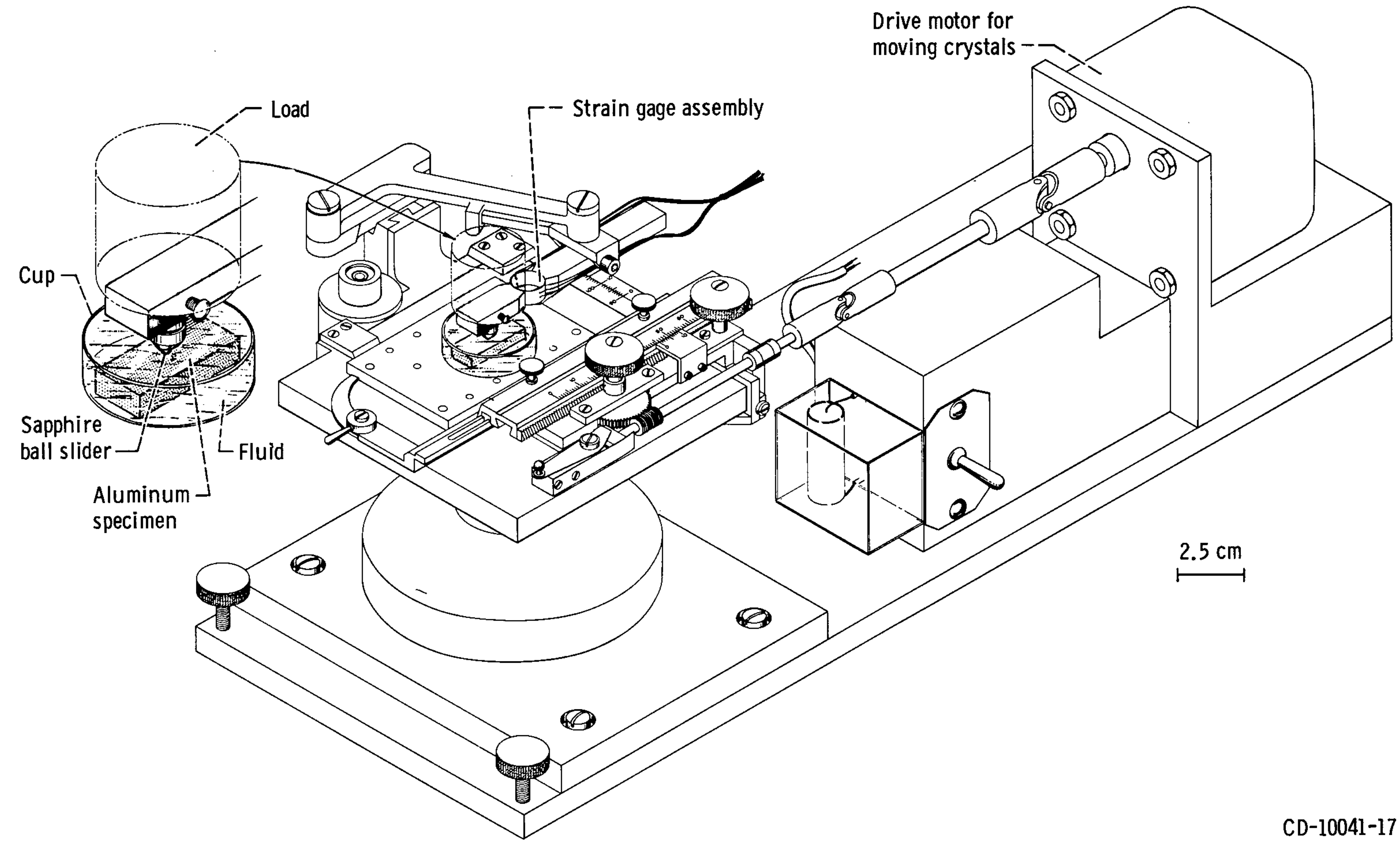


Figure 1. - Sliding friction apparatus.

Materials

The single crystal and polycrystalline aluminum used in these studies was 99.999 percent purity. The mercury used was triple distilled and the metals cadmium, zinc, gallium, and thallium were 99.999 percent or higher purity. The organic solvent hexadecane was 99+ percent pure and was free of olefins. Prior to its use, it was percolated through silica-gel. The other organics were all reagent grade.

Experimental Procedure

The aluminum polycrystalline samples were machined into rectangular specimens 25 millimeters long by 12 millimeters wide and 6 millimeters high. The surfaces were polished on silicon carbide papers. They were then polished with diamond paste. Specimens were subsequently annealed at 500° C for $1\frac{1}{2}$ hours. The specimens were electropolished in orthophosphoric acid. For the experiments in which preoxidized surfaces were employed, oxidation was achieved by the technique of references 16 and 17. Film thickness was determined by the standard frit technique used in anodizing (ref. 18).

The single crystals flat specimens were electric discharge machined to 25 millimeters by 6 millimeters thick wafers which were also polished on papers, with diamond paste, electropolished, annealed, and re-electropolished. The single crystal orientations specified are within $\pm 2^{\circ}$ of the orientation indicated and were determined by the Laue X-ray technique.

After electropolishing or oxidizing, the metal specimens were placed in a quartz vacuum tube and the residual absorbates were driven from the aluminum surface by heating. After the specimens were cooled to room temperature under vacuum, the liquid medium of the experiment was bled into the vacuum system. From this point of the procedure until the completion of the friction experiment, the specimen remained under the liquid medium.

Experiments conducted to determine the anisotropic friction characteristics of aluminum were made with aluminum rider specimens in order that shear rather than plowing effects could be measured during sliding. Since very light loads were employed in these experiments the amount of surface deformation was small and wear is reported as width of the wear track generated.

With the use of sapphire sliders, the influence of environmental constituents on the surface deformation during sliding were more readily discernable. Since with a sapphire ball as the rider, plastic deformation of the aluminum surface occurs during sliding, the effect of the slider on the aluminum is reported as plastic deformation. The plastic deformation was determined from surface profile traces.

RESULTS AND DISCUSSION

Anisotropic Friction and Wear of Aluminum

Single crystals of aluminum. - The friction properties of three crystallographic planes of aluminum were examined. The planes were the {100}, {110} and the {111}. Sliding was restricted to the ⟨110⟩ direction on all three planes to determine the effect of plane alone on friction and wear. The results obtained are presented in figure 2. The data of figure 2 indicate that the friction and wear are anisotropic. Friction was lowest on the {111} planes and greatest on the {100} planes. These friction results agree with data obtained for copper, another face centered cubic metal in an earlier investigation (ref. 5). The track width was greatest on the {111} plane and least on the {100} plane.

Friction and wear were not only a function the crystallographic plane on which sliding took place but also a function of direction. Sliding experiments conducted on the {110} planes of aluminum in two crystallographic directions the ⟨100⟩ and ⟨110⟩ revealed marked differences in friction and wear with change in crystallographic direction as is shown in figure 3. On the {110} planes both friction and wear were higher in the ⟨110⟩ direction than in the ⟨100⟩ direction. As indicated by the data, the difference is substantial.

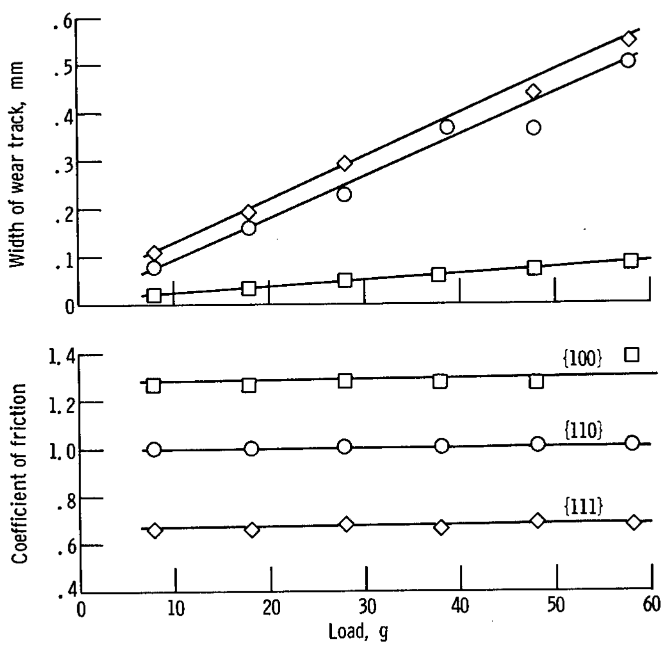


Figure 2. - Friction coefficient and width of the wear track on various planes of aluminum. Sliding direction, ⟨110⟩; sliding velocity, 0.005 millimeter per second; experiments conducted in air at 20° C.

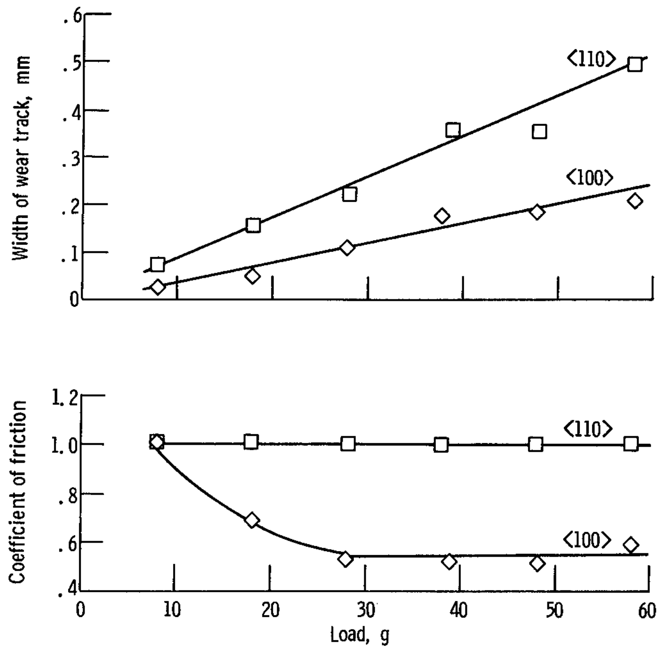


Figure 3. - Friction coefficient and width of wear track for sliding friction experiments on {110} plane of aluminum. Rider, {110} plane of aluminum; sliding velocity, 0.005 millimeter per second; experiments conducted in air at 20° C.

Polycrystalline Aluminum

The friction and wear of aluminum has also been found to be anisotropic for textured polycrystalline rolled sheet. The cube texture in rolled aluminum is, in reality, a shear texture which arises as a result of the high friction between the metal and rolls. When sliding on such a sheet, friction and wear are found to be lower normal to than in the direction of rolling as indicated by the data of figure 4. Microhardness measurements in the wear track normal to the rolling direction after a single pass of the rider indicates that the hardness is 20 percent greater than that in the wear track parallel to the rolling direction.

The results of figure 4 are as might be anticipated since tensile and yield strengths are normally greater and ductility lower normal to than parallel to the rolling direction for face centered cubic metals such as aluminum. The degree of anisotropy will be a function of the amount of reduction by rolling. There was a 50-percent reduction for the specimens of figure 4. If the amount of reduction were increased say to 90 percent, an even greater difference in friction and wear might be anitcipated.

The texturing referred to in figure 4 for aluminum is a "crystallographic fibering" (preferred orientation of planes). This must be distinguished from a mechanical type of

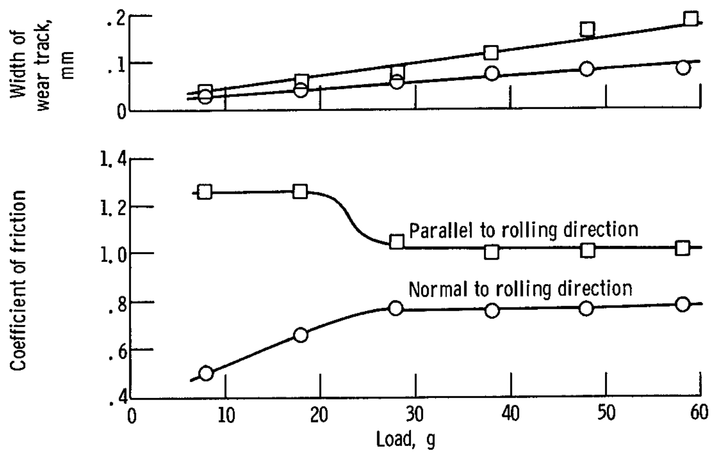


Figure 4. - Friction coefficient and width of wear track for sliding friction experiments on <100> textured, rolled, polycrystalline aluminum sheet. Rider, {100} plane of aluminum; sliding velocity, 0.005 millimeter per second; experiments conducted in air at 20° C.

fibering which develops in forging and is observed in the fabrication of balls for ball bearings (ref. 19).

Influence of Embrittling Environments

It is well known that liquid metals have the capacity to embrittle many engineering metals and alloys (ref. 15). In order to determine the influence of this embrittling effect on friction and surface deformation during sliding, experiments were conducted under mercury and mercury containing various other metals with single crystals and polycrystalline aluminum specimens. Results obtained for sliding experiments in air, mercury, and mercury with 3 atomic percent of cadium, zinc, gallium, and thallium are presented in table I.

An examination of table I indicates that, in mercury, the friction coefficient for aluminum was the same as in air. The amount of relative plastic flow of the aluminum under the sapphire, however, was two and one half times greater in air than in mercury. This marked difference is believed to be due to two phenomena. First, mercury embrittles the surface, reducing its ability to deform plastically; second, in air (with moisture present, 30 percent relative humidity), the aluminum will deform plastically more readily than in the absence of moisture. This latter effect, the "Rebinder Effect" will be discussed in more detail later.

TABLE I. - INFLUENCE OF EMBRITTLING ENVIRONMENTS

ON FRICTION AND DEFORMATION OF

POLYCRYSTALLINE ALUMINUM

[Load, 250 g; sliding velocity, 0.005 mm/sec; 20° C; single pass of sapphire slider across aluminum surface.]

Environment	Coefficient of friction	Relative plastic deformation
Air	1.0	25.0
Mercury	1.0	10.0
Mercury and 3 at. % cadmium	.30	12.0
Mercury and 3 at. % zinc	.50	6.0
Mercury and 3 at. % gallium	.82	11.0
Mercury and 3 at. % thallium	.24	6.0

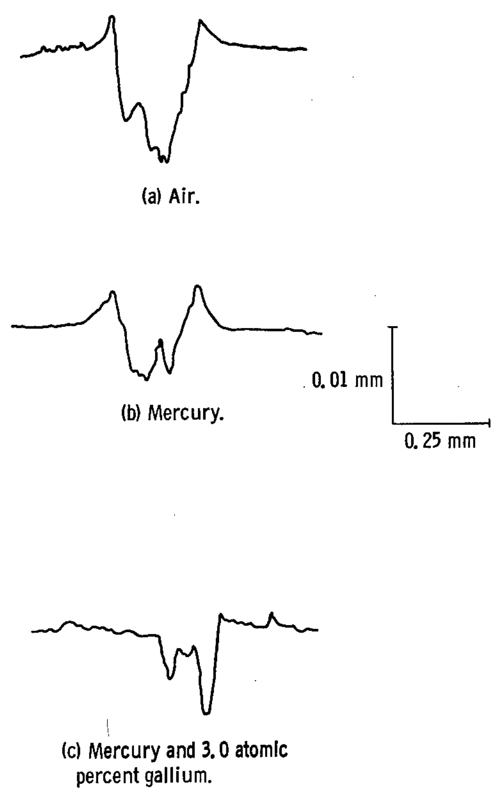


Figure 5. - Surface profiles of deformed aluminum surfaces in various media. Load, 250 grams; sliding velocity, 0.005 millimeter per second; temperature, 20° C; single pass of sapphire slider.

The presence of 3 atomic percent cadmium or gallium did not reduce surface deformation but had essentially the same effect as mercury. With the addition of 3 atomic percent zinc or thallium to mercury, a marked reduction in both surface deformation and friction occurred compared to the results obtained in mercury alone. The relative amount of surface deformation in three environments, air, mercury, and mercury with 3 atomic percent gallium are shown in figure 5.

Experiments were conducted with various atomic percent of thallium in mercury to determine the effect of thallium concentration on deformation and friction of aluminum. The results obtained in these experiments are presented in figure 6. With only 0.1 atomi percent thallium, a reduction in surface deformation and a marked reduction friction

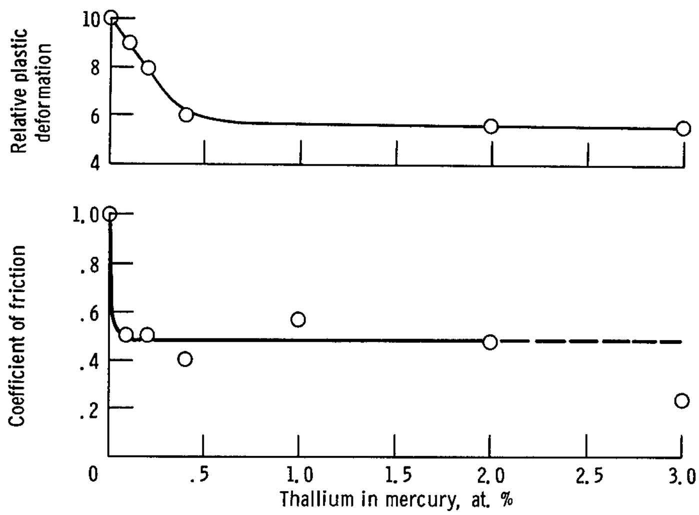


Figure 6. - Coefficient of friction and relative plastic deformation of aluminum in mercury containing various atomic percent thallium. Load, 25 grams; sliding velocity, 0.005 millimeter per second; temperature, 20° C; single pass of sapphire slider across surface.

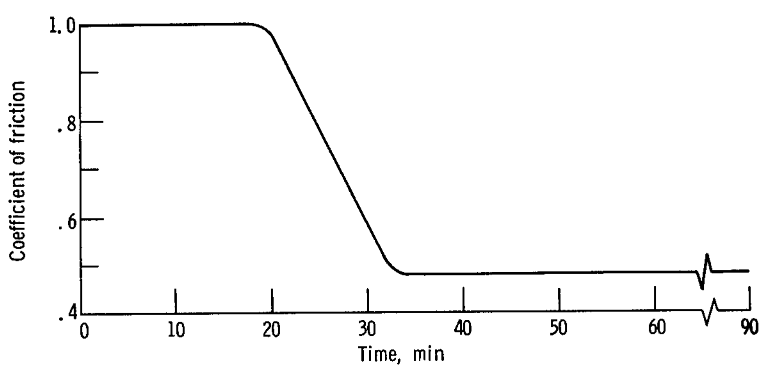


Figure 7. - Coefficient of friction for aluminum in mercury - 2 atomic percent thallium environment as function of time. Load, 250 grams; sliding velocity, 0.005 millimeter per second; temperature, 20° C.

occurred. Beyond 0.4 atomic percent thallium, no change in relative deformation was noted. It is of interest to note that, of the four metals, cadmium, zinc, gallium, and thallium, the metal thallium has the highest solubility in mercury and is insoluble in aluminum.

The embrittlement of a surface is a time dependent effect as is shown in the friction data of figure 7. The coefficient of friction for aluminum in mercury - 2 atomic percent thallium was initially the same as that obtained in mercury in table I. The friction coefficient was relatively constant and after 20 minutes began to decrease due to surface effects produced by the thallium. When the liquid metal had been in contact with the aluminum surface for 35 minutes, the friction coefficient had decreased half the initial value.

In all of the experiments conducted under liquid metals, no evidence of surface cracks were found in or about the track generated on the aluminum surface by the sapphire rider. Etch pitting of the surface after the experiment revealed considerable plastic flow had occurred as indicated by the photomicrograph of figure 8. Dislocation density was so great in the sliding track that individual pits could only be discerned near the track edge.

Figure 8. - Etch-pitted wear track in grain of polycrystalline aluminum. Track generated under mercury - 2 atomic percent thallium. Load, 250 grams, sliding velocity, 0.005 millimeter per second; temperature, 20° C.

TABLE II. - INFLUENCE OF 2 ATOMIC PERCENT THALLIUM IN MERCURY ON FRICTION AND DEFORMATION OF ALUMINUM

[Load, 250 g; sliding velocity, 0.005 mm/sec; 20° C; single pass of sapphire slider across surface.]

Aluminum flat form	Coefficient of friction	Relative plastic deformation
Polycrystal aluminum	0.48	6.0
Single crystal (111)⟨110⟩	0.48	10.5

The etch pits of figure 8 were in one large grain of a polycrystalline specimen.

Sliding friction experiments were conducted with mercury - 2 atomic percent thallium using an aluminum single crystal; sliding on {111} planes and in the ⟨110⟩ directions. The relative surface deformation and the friction coefficient obtained are presented together with the polycrystalline data in table II. Examination of table II indicates that, while the friction coefficients were essentially the same for the two forms of aluminum, a greater degree of deformation occurred on the single crystal surface. These results are as might be anticipated from the increased plasticity of single crystals.

The Influence of Organic Surface Active Agents on the Friction and Deformation of Aluminum

Effect of organic acid concentration. - While much is known about the ability of various surface active organic molecules to reduce friction and wear in metals, little is known about the influence of these molecules on plastic deformation during sliding. There are effects on mechanical properties (refs. 8 to 10). Experiments were, therefore, conducted with a hard sapphire slider sliding on polycrystalline aluminum in hexadecane and hexadecane containing various concentrations of oleic acid. The amount of deformation to the aluminum surface, as determined by the surface profilometer, is presented in the data of figure 9. The data of figure 9 are for an electropolished polycrystalline aluminum surface. Such a surface has a 25 Å thick amorphous aluminum oxide film. Figure 10 shows the slip bands along the wear track and that slip has occurred on more than a single slip system.

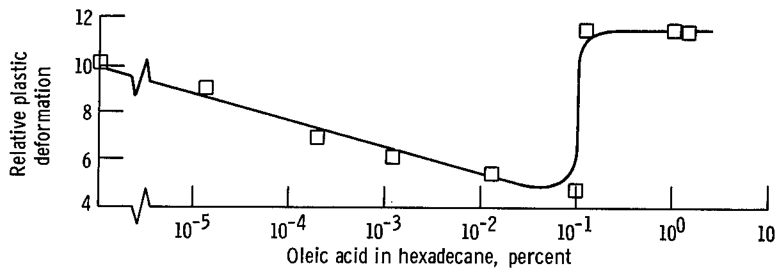


Figure 9. - Relative plastic deformation of electropolished aluminum (oxide film, 25 Å thick) in hexadecane with various concentrations of oleic acid. Load, 250 grams; sliding velocity, 0.005 millimeter per second; temperature, 20° C; single pass of sapphire slider across surface.

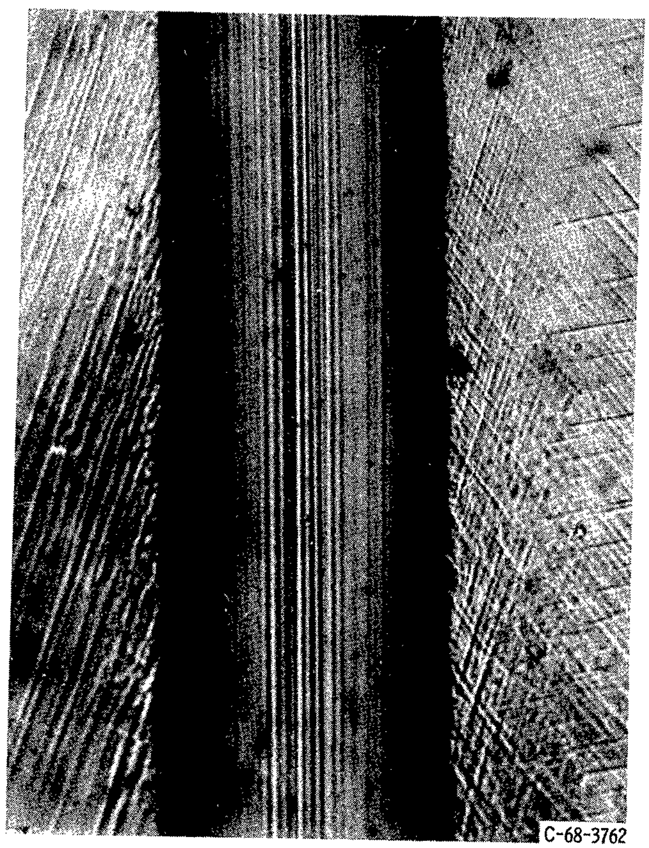


Figure 10. - Photomicrograph of wear track on grain of polycrystalline aluminum. Lubricant, hexadecane with 0.2 percent oleic acid; load, 250 grams, sliding velocity, 0.005 millimeter per second.

The data of figure 9 indicate a decrease in the amount of plastic deformation with acid concentration to 10^{-1} percent. At an acid concentration of 2.0×10^{-1} percent, the deformation increased sharply to a value greater than that observed in pure hexadecane. The reduction in deformation with increase in acid concentration is what might normally be anticipated; the sudden increase at 2.0×10^{-1} percent oleic acid would not. This

increase in deformation is believed to reflect the "Rebinder Effect," a reduction in the yield stress of the aluminum in the presence of chemisorbable species. The reduction in yield stress with surface active species is very sensitive to concentration effects of the adsorbing species (refs. 10 to 14). The necessity of achieving a concentration of 2×10^{-1} percent oleic acid before a manisfestation of the "Rebinder Effect" is observed is therefore in keeping with the mechanism associated with this concept.

Rebinder Effect

The "Rebinder Effect" has been explained by Rebinder as an increase basically in the plasticity of a material because of a reduction in the surface energy associated with the adsorption of surface active species. This explanation is inadequate and recently others have attempted explanations for the observed effects (ref. 13). From a lubrication point of view its important to know the influence of the effect on materials in sliding contact even if the mechanism is not throughly understood.

Considerable controversy has existed through the years as to the existence of the "Rebinder Effect" in metals (ref. 20). In reference 20 it is felt that surface oxides are necessary on metals in order that the "Rebinder Effect" influence deformation. This is not, however, in harmony with Rebinder's own experimental observations where the effect was measured for tin crystals freed of surface oxide (ref. 9).

The mirror like surface of the electropolished aluminum used in this study contained an oxide 25 Å thick. If oxides are important to the "Rebinder Effect," then increasing the surface oxide thickness, that is, oxidizing the surface, may exert an influence on observed surface deformation (ref. 21). The experiments of figure 9 were therefore repeated with a 100 Å aluminum oxide film present on the surface. These experiments will be discussed later.

The work of reference 21 has shown that surface films present on aluminum will influence mechanical deformation of the aluminum. The rate of work hardening of aluminum has been found to be influenced by the presence or absence of surface oxides. According to references 22 and 23, the rate of work hardening is reduced if oxidation of aluminum is prevented.

Aluminum oxide itself, which is present on an aluminum surface, is very sensitive to the presence of adsorbed surface films. Reference 21 indicates that stripped aluminum oxide films present on aluminum surfaces undergo a four fold increase in Young's modulus when adsorbed water is removed. In reference 14, a marked reduction in the hardness of aluminum oxide was found with water vapor present. These latter observations on the behavior of aluminum oxide in the presence of adsorbates are evidence of the "Rebinder Effect" in aluminum oxide.

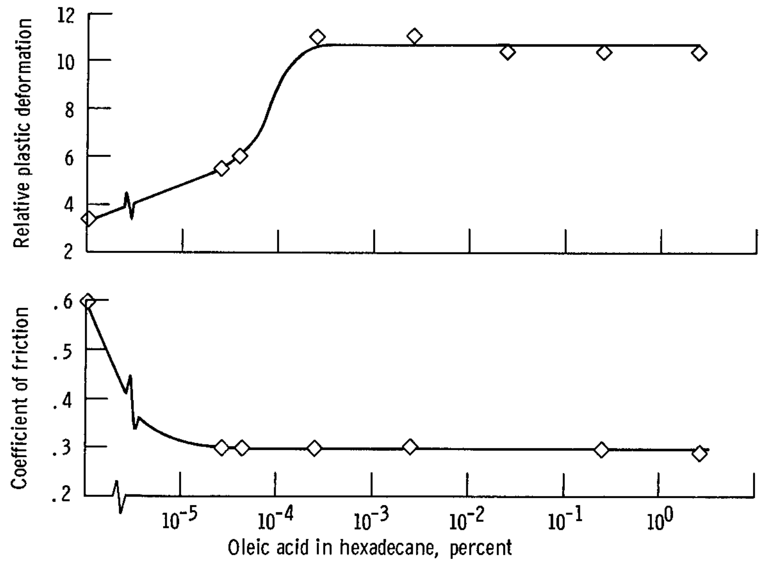
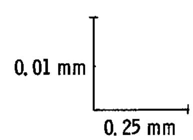


Figure 11. - Coefficient of friction and relative plastic deformation of oxidized (100 Å thick oxide) aluminum in hexadecane with various concentrations of oleic acid. Load, 250 grams; sliding velocity, 0.005 millimeter per second; temperature, 20° C; single pass of slider across surface.

(a) Electropolished aluminum (25-Å oxide) in hexadecane.



(b) Oxidized aluminum (100-Å oxide in hexadecane.

(c) Oxidized aluminum in hexadecane with $2x10^{-3}$ percent oleic acid.

Figure 12. - Surface profiles of deformed aluminum surfaces in various media. Load, 250 grams; sliding velocity, 0.005 millimeter per second; temperature, 20° C; single pass of sapphire rider.

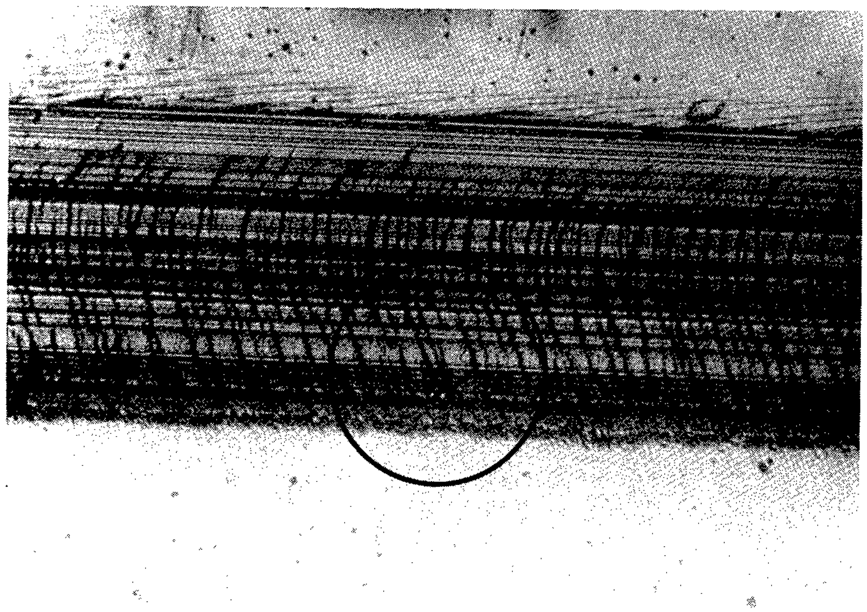
Influence of Surface Active Organics on Oxidized Aluminum

The results of sliding experiments on an aluminum surface with 100 Å of aluminum oxide present are shown in figure 11. It is of interest to note the marked difference in the relative surface deformation with increase in acid concentration. There is a very large increase in surface deformation of acid concentrations to 10^{-4} percent. Beyond that concentration deformation, was hardly affected by increasing amounts of acid. Note that, with the thicker film of oxide, a lower acid concentration was necessary to influence surface deformation (see fig. 9). The friction coefficient as a function of acid concentration is also presented in figure 11. The friction coefficient decreased to 0.3 at an acid concentration of 10^{-5} percent. This decrease may be associated with the reduction in the adhesion of aluminum metal to the aluminum oxide rider.

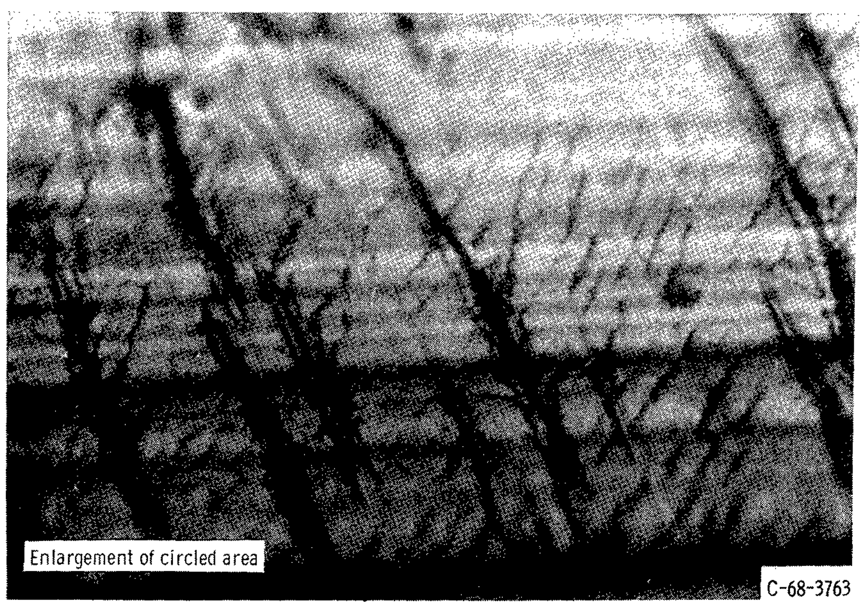
Figure 12 indicates the relative amounts of plastic deformation that occurred to the surface of aluminum during these experiments. Figure 12(a) indicates that the surface deformation is greater under a fixed load of 250 grams in the electropolished (25 Å oxide) than with 100 Å of aluminum oxide present (fig. 12(b)). When oleic acid is added to hexadecane an increase in surface deformation of oxidized aluminum occurs (fig. 12(c)).

With the 100 Å thick oxide present on the aluminum surface, surface cracks were noted with experiments conducted in hexadecane. The presence of these cracks are shown in the two photomicrographs of figure 13. The upper photograph shows the extent of crack formation and the lower photograph is an enlargement of the cracks in a selected area of the wear track.

Experiments were conducted with single crystals of aluminum in the electropolished and oxidized states in hexadecane and hexadecane containing oleic acid. Sliding was on the $\{111\}$ planes in the $\langle 110 \rangle$ direction. The results obtained are presented in table III together with polycrystalline results for comparative purposes. The data of table III indicate that, while differences in friction and deformation of single crystal and polycrystalline specimens exist for both forms of aluminum (single crystal and polycrystalline), the presence of oleic acid on the oxidized aluminum surface results in an increase in the amount of surface deformation.



0.6 mm



0.2 mm

Figure 13. - Surface cracks developed in sliding region on aluminum with 100-Å-thick oxide of aluminum present. Lubricant, hexadecane; load, 250 grams; sliding velocity, 0.005 millimeter per second; temperature, 20° C.

TABLE III. - INFLUENCE OF ORGANIC SURFACE ACTIVE AGENTS ON FRICTION

AND DEFORMATION OF ALUMINUM

[Load, 250 g; sliding velocity, 0.005 mm/sec; temperature 20° C; single pass of sapphire slider across surface.]

Metal form	Hexadecane		Hexadecane and 0.2 percent oleic acid		Hexadecane		Hexadecane and 0.2 percent oleic acid	
	Electro-polished	Oxidized	Electro-polished	Oxidized	Electro-polished	Oxidized	Electro-polished	Oxidized
	Coefficient of friction				Relative plastic deformation			
Polycrystal aluminum	0.60	0.60	0.54	0.29	10.0	3.5	4.8	10.5
Single crystal (111)⟨110⟩	.94	.40	.50	.20	8.0	3.0	9.0	22.5

Effect of Organic Acid Chain Length

The deformation of aluminum appears to be sensitive to the concentration of surface active agent. Experiments were conducted to determine if the chain length of an organic acid had any influence on surface deformation. Results obtained with a series of acids from formic to stearic are presented in figure 14. Increasing the chain length up to C-12 results in an increase in the amount of surface deformation of oxidized polycrystalline aluminum. Beyond C-12 no further increase in deformation was observed. These results indicate that surface deformation is influenced not only by acid concentration but also by chain length.

Friction coefficients were also measured as a function of acid chain length and are presented in figure 14. The friction coefficient decreased to a C-12 chain length and then remained relatively unchanged at greater chain lengths. These results are very similar to those obtained in reference 24 in lubricating steel surfaces with pure alphatic acids of various chain lengths.

Effect of Alcohol Chain Length

The influence of the chain length of alcohols and their ability to affect surface deformation was also investigated. The results obtained in some of these experiments are presented in figure 15. In figure 15 the alcohols were added to hexadecane at a concen-

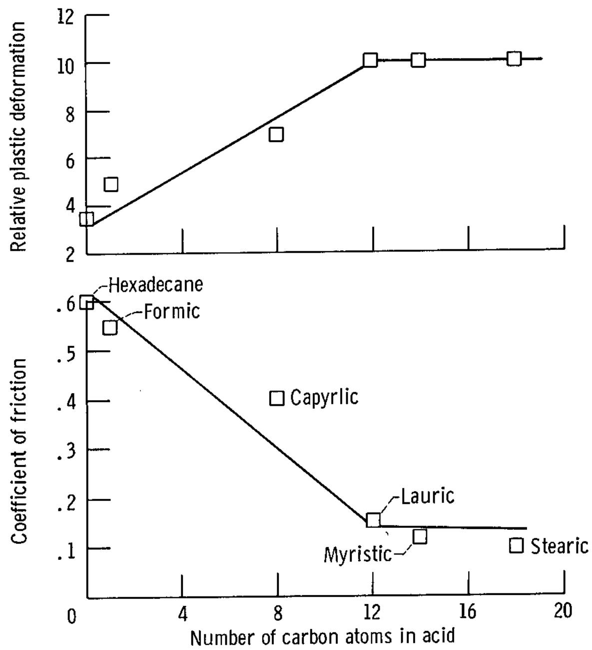


Figure 14. - Coefficient of friction and relative plastic deformation of oxidized aluminum (100-Å oxide) in 0.15 mole per liter of various acid-hexadecane media. Load, 250 grams; sliding velocity, 0.005 millimeter per second; temperature, 20° C; single pass of slider across aluminum.

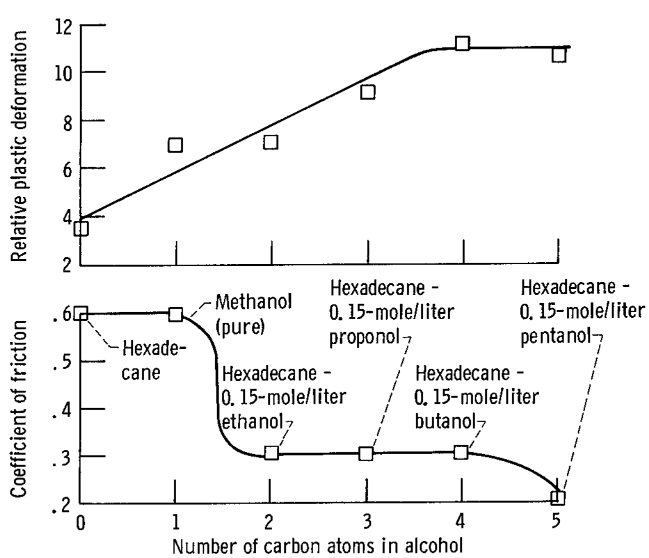


Figure 15. - Coefficient of friction and relative plastic deformation of oxidized (100-Å oxide) aluminum in various media. Load, 250 grams; sliding velocity, 0.005 millimeter per second; temperature, 20° C; single pass of sapphire slider across aluminum surface.

tration of 0.15 mole per liter, except for methanol. Pure methanol was used because it is not soluble in hexadecane. The results of figure 15 indicate that, as with acids, the amount of surface deformation increased with chain length. The coefficient of friction did not, however, decrease in a linear manner.

Influence of Alloying

If the oxide of aluminum is necessary for the observation of the "Rebinder Effect" it would be of interest to know if aluminum oxide must necessarily be present on aluminum or will other metals alloyed with aluminum exhibit the same behavior. Alloys were therefore prepared with various atomic percents of aluminum in silver. The surface of the specimens were oxidized and friction experiments were conducted under hexadecane and hexadecane containing 0.2 percent oleic acid. The results obtained are presented in figure 16. It should be noted in figure 16 that with pure silver the presence of the acid appeared to have no effect on surface deformation. Similar results were obtained with 0.3 atomic percent aluminum in the silver. At 0.9 atomic percent and higher concentrations, surface deformation was greater in the presence than in the absence of oleic acid. These experiences are significant. Friction coefficient was lower for all specimens in the presence of the acid.

Examination of the surface of silver revealed silver oxide (AgO). With the alloys of 1.0 atomic percent silver and above aluminum oxide (Al_2O_3) was detected on the surface.

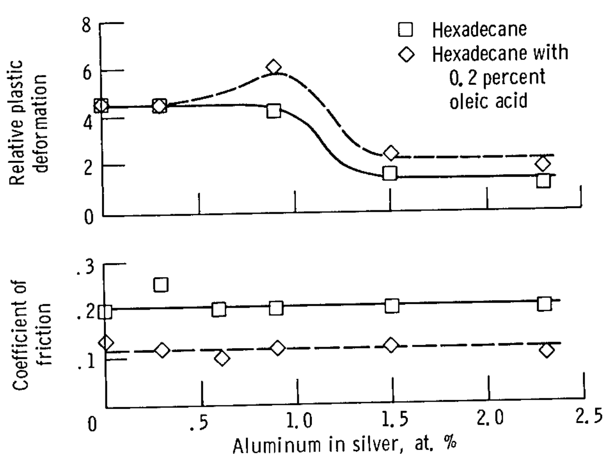


Figure 16. - Coefficient of friction and deformation of oxidized aluminum-silver alloy surfaces in two media. Load, 250 grams; sliding velocity, 0.005 millimeter per second; temperature, 20° C; single pass f sapphire slider across aluminum surface.

SUMMARY REMARKS

Based on the data obtained in this investigation with single and polycrystalline aluminum in various environments the following summary remarks are made:

1. Influence of orientation:

a. The friction and wear of aluminum, is highly anisotropic. With single crystals, friction and wear were found to be a function of plane and of crystallographic direction of sliding.

b. The friction and wear of textured polycrystalline aluminum sheet was also found to be anisotropic. Friction and wear were lower normal to than in the direction of rolling.

2. Influence of liquid-metal environment:

a. In sliding experiments under mercury the amount of surface deformation was less than observed in equivalent experiments in air.

b. The presence of small concentrations of more active embrittling metals such as zinc and thallium in mercury reduced further the amount of surface deformation observed during sliding.

c. Despite the embrittling nature of liquid metals to aluminum, no evidence of crack formation was observed to have taken place on the aluminum surfaces.

3. Influence of organic surface active agents:

a. The surface deformation of aluminum during sliding was found to be influenced by the presence of surface active agents such as organic acids and alcohols. Their presence increased surface deformability (see section Rebinder Effect).

b. With electropolished aluminum surfaces (oxide film 25 Å thick) an increase in surface deformation in the presence of a surfactant was found to be concentration dependent with organic acids. When the aluminum surface was oxidized (oxide film 100Å thick) an increase in surface deformability (see section Rebinder Effect) was observed over a wide range of acid concentrations.

c. The ability of organic acids and alcohols to increase surface deformation during sliding was found to be a function of carbon chain length in the acid or alcohol.

d. While the "Rebinder Effect" was not observed with silver, the alloying of silver with aluminum and subsequent surface oxidation resulted in an observation of this effect.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, October 25, 1968,
129-03-13-09-22.

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